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Presented at the USACE Seventh Remote Sensing Symposium, 7-9 May 1990, Portland, OR.

HYPERSPECTRAL IMAGERY - WHAT IS IT? - WHAT CAN IT DO?

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ABSTRACT

Because all materials reflect, absorb, or emit photons in ways characteristic of their molecular makeup, a high resolution trace of the intensity of the transmitted, reflected, emitted, or luminesced radiation versus wavelength forms a graphical record unique to a given material. The laboratory use of spectral measurements to identify minerals, pigments, and organic and inorganic compounds is an established and reliable technique; and, the reasoning goes, if such could be done from air or space, it would give remote sensing a similar capability. Unfortunately, the useful absorption bands are narrow, 10 nanometers (nm) or less, and cannot be recorded with broad band systems such as Landsat. With the advent of the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and similar systems, the narrow band capability entered the remote sensing domain. AVIRIS is a true spectrometer, collecting reflected solar energy (0.4-2.5 micra) in about 220 channels, or images, each in a spectral bandwidth of about 9.6 nm. This type of narrow band information is called hyperspectral. In support of using hyperspectral systems for targeting, the U.S. Army Engineer Topographic Laboratories (USAETL) has developed a series of spectral reflectance, luminescence, and thermal infrared data bases of field and laboratory measurements of some 1,000 samples of soils, rocks, vegetation, and foreign and domestic camouflage materials. No technique is a panacea, and the hyperspectral systems are no exception; but, from the standpoint of targeting, they have potential beyond any previous remote sensor.

INTRODUCTION

Although a variety of energy forms are available for remote sensing, such as electromagnetic, gravity, the magnetic field, the electrical field, radio activity, acoustics, etc., electromagnetic energy accounts for probably 95 percent of the applications. Within the electromagnetic spectrum, the most used portions are the visual, photographic, infrared thermal, passive microwave, and active microwave, or radar - and, within these domains, the most common presentation of the information is as an image, or a collection of images from different bands. Whatever the image, the recorded tones represent intensity variations in reflected, emitted, or luminesced photons, depending on what remote sensing system was used.

Techniques for extracting information from these images range from the simple to the complex; and from manual, through man-computer interaction, to automated procedures. The methodology used depends on the intended application - i.e., are you after general terrain information, or targeting information? Although there is a broad overlap, the former relies on manual analysis of imagery, and the latter on computer assistance.

Reliable and detailed information about any region of the earth in terms of its composition, structure, properties, conditions, use, and probable response to stress, are the fundamental factors needed for evaluating the terrain for such endeavors as engineering site selection and evaluation, locating

engineering materials, environmental impact predictions, predicting terrain characteristics for cross-country movement, and selecting potential ground water sites and subsurface waste disposal sites, to name but a few. The determination of these factors is based on the manual, or "eyeball," evaluation of shape patterns, especially three-dimensional shapes, such as landform and drainage, augmented by an evaluation of the patterns of vegetation, lineations, and tone and texture. For obtaining this type of information, the manual analysis of stereo imagery is still state-of-the-art (Rinker and Corl, 1984, 1989). Digital analysis can contribute very little.

Targeting, on the other hand, is a very different matter. This refers to the detection and possible identification of specific features, and this requires that the target have some characteristic that differs from its background and that cannot be confused with any other feature in the field of view. Detection based on shape, size, and arrangement, includes such examples as roads, airports, dams, vehicles, crop/field patterns, structures, and urban areas; and such are usually easier to perceive by manual analysis. In addition to shape, differences can also be based on color, spectral reflectance, spectral emittance (temperature), luminescence, acoustical reflectance and emittance, magnetic fields, etc. Application examples include road type (asphalt or cement concrete), diseased vegetation, flood boundaries, wetland areas, thermal springs, thermal plumes from power plants, oil slicks, hot spots in burned areas, alteration zones, number of lakes in a region, camouflaged sites, and military units and equipment. Included in targeting are the applications of change detection and monitoring, e.g. seasonal changes in wetlands, desertification, alteration of land use, forest clearing, extent of pack ice, etc. Although aerial photography and multi-band images are used in these tasks, it is within this domain that computer assisted techniques and digital analysis become not only dominant, but imperative.

In order to improve remote sensing capabilities, especially those associated with targeting, there has been a steady trend over the years to use narrower spectral bandwidths to record reflected, luminesced, and emitted photons. The rationale in support of this evolution is the fact that, in general, the finer the slice of spectral data, the greater the ability to establish identities and conditions.

RADIATION - THE CARRIER OF INFORMATION

When electromagnetic radiation falls on a material (gas, liquid, or solid) several things can happen - singly or in combination. What happens depends primarily on the electrical properties of the materials, i.e., the index of refraction, or dielectric constant. More exactly, it depends on changes in the electrical properties between the medium the radiation is in, and the medium it is entering. If, in going from one medium to another, the radiation encounters a change in electrical properties that takes place in a distance less than its characteristic wavelength, then something must happen to that radiation - it cannot continue as it was. It will undergo, singly or in combination, reflection (scattering), refraction, or absorption.

Scattering and absorption are important, because they alter the intensities of the wavelength distribution of the energy reflected to the sensor. The recording of this reflected component is the most common form of remote sensing, and can involve the sun, lasers, and radio frequencies, i.e., radar.

The sun is the most frequently used source and supports sensors such as cameras, the Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) bands 1, 2, 3, 4, 5, and 7, SPOT, and the hyperspectral systems. The sun is a full blackbody radiator, emitting energy from the short wavelength ultraviolet, through the visible and infrared, and out to the longest wavelengths in the radio region. Some 96 percent of the sun's energy, however, is emitted at wavelengths shorter than 2.5 micra. At wavelengths longer than this, one enters the thermal infrared domain and the need for different types of detectors. Although there is still a reflected solar component, it is small compared to the thermally emitted signal. For wavelengths shorter than about 0.35 micra, or 350 nm, the atmosphere greatly attenuates the incoming photon flux. Thus, the reflected solar spectrum is generally considered to cover the 0.4 to 2.5 micra range; a spread that contains about 84 percent of the sun's energy.

Radiation absorbed by a material leads to other effects. For one, the absorbed photons can increase the internal energy, or temperature, of the material, which, in turn, increases the quantity and alters the wavelength distribution of the thermally emitted radiation, both infrared and microwave. This is the most common outcome of absorption, and is the basis for thermal, or passive, remote sensing. The thermal infrared techniques are associated with the 3.5-5.5 and 8-14 micra bands because the atmosphere is relatively transparent to those wavelengths. The passive microwave bands are the K, X, C, P, L, etc. - bands also used by active microwave systems, i.e., radar. Unlike reflected solar radiation contrast, thermal contrast in the terrain is influenced by a variety of diurnal and seasonal variations in climatic and meteorological factors such as wind, atmospheric pressure, dew, rain, incoming space radiation, etc. For a variety of reasons, aside from military targeting, which cannot tolerate time constraints, thermal infrared missions are best flown at night.

A second effect of photon absorption is luminescence. This will be dwelt on more than reflectance and absorptance, because it is not as well known and, although useful as a remote sensing technique, it has had but limited recognition. There are materials that can absorb photons of one frequency and emit photons of a lower frequency, i.e., lower energy, without any significant increase in temperature. These materials are said to be luminescent. An example is the emission of visible light from minerals when they are illuminated with "black" light, or ultraviolet radiation. Luminescence is an emission of radiation due to electronic transitions, and there are two kinds - fluorescence and phosphorescence. In a general sense, the distinctions are made on the basis of time - i.e., how long does the light last after the excitation energy is turned off? This is called the decay time. In fluorescence, the decay time is very short, ranging from 10^{-9} to 10^{-3} seconds. For example, the fluorescence decay time of rhodamine B in water is about 2.5 nanoseconds (ns). In phosphorescence, the decay time is longer, i.e., greater than 10^{-3} seconds - and sometimes much longer. Calcium sulphide, for example, can continue to glow for several hours after the excitation illumination is turned off.

Luminescent techniques require an excitation energy source to induce emission, and darkness in order to detect the luminesced photons. Fortunately, the sun meets both of these needs - as does the nighttime use of lasers. The sun does not emit a continuous spectrum, i.e., energy at all wavelengths, or frequencies. Although such is generated in the hot core, electronic

absorption by elements and ionized atoms in the cooler outer envelope greatly reduces the intensities of many of the frequencies. When the sun is examined with a good spectroscope, one finds that there are gaps - many gaps - wherein energy is greatly reduced, or absent. These gaps of darkness are very narrow in bandwidth - so narrow they are called lines. Specifically, they are called Fraunhofer Lines in honor of their discoverer. The spectral bandwidths of these lines are measured in Angstrom Units, frequently in small fractions of Angstrom Units. The ultraviolet, visible, and near infrared portions of the solar spectrum contain over 30,000 Fraunhofer Lines, or lines of darkness. These lines provide the darkness needed for detection of the luminescence, and the sun's illumination on the short wavelength side of the lines provides the excitation energy.

A sensor system that can look at both the sun and the earth's surface with detectors sensitive to energy in these dark lines, can detect the presence of luminesced photons from the earth's surface, or target. If, from the target, it detects a certain intensity in a dark line band, it cannot be reflected solar energy because such is not coming from the sun. The fill-in must, therefore, be due to luminesced photons from the target. Such is the function of the Fraunhofer Line Discriminator (FLD) previously mentioned (Hemphill and Settle, 1980, and Hemphill, et al., 1989).

No matter what sensor is used, there are other factors that influence the signal that one wants to detect. The atmosphere itself can remove energy from the sunlight, as well as add its own component - luminesced induced, thermally induced, or scattered. Wind and atmospheric pressure changes can greatly alter infrared thermal contrast, and make it possible or impossible to detect some kinds of targets. Such things as temperature and pH can alter the characteristics of the luminesced photons. Some materials that are under constant, or steady-state illumination, give a different luminescence signal after an hour or two, than they do to an instant measurement immediately after excitation. These changes show as an increase in intensity at longer wavelengths of emission and a decrease of the shorter wavelength components. In fact, some molecules show little luminescence when first illuminated, but develop an intense emission after steady-state illumination. These characteristics are usually associated with liquids and are indicative of changes caused by chemical reactions. Also, the recorded emission spectrum can be distorted in the short wavelength region by self-absorption within the solution. Whether or not these factors are of concern to remote sensing of earth surface and targeting materials is moot. Some materials, such as vegetation, have a near surface liquid component, and chemical reactions are going on - e.g., photosynthesis. Furthermore, these surfaces are receiving steady state illumination from the sun for hours. In laboratory measurements, the illumination, i.e., the excitation mode, is of short duration. Another characteristic of luminescence is that for any specific wavelength of excitation, there is an emission spectra that can take place over a fairly broad wavelength band, and the decay times of the longer wavelengths can be considerably longer than those of the shorter wavelengths. The total is still a very short time. In laboratory experiments, decay time spectra have shown links to material types and conditions. Whether or not such has application in remote sensing remains to be determined.

Because all materials reflect, absorb, or emit photons in ways characteristic of their molecular makeup, a high resolution trace of the intensity of

the transmitted, reflected, emitted, or luminesced radiation versus wavelength forms a graphical record unique to a given material. Different materials cannot have identical spectral wave shapes of reflectance, emittance, and luminescence. These characteristic absorption and emission bands occur in narrow wavelength ranges, 10 nm or less; and, unless the instruments have that kind of spectral resolution, these details cannot be recorded. Although many laboratory and field instruments exceed this spectral resolution, airborne systems have only recently entered this domain. From a laboratory point of view, the use of spectral measurements to identify and/or assay components of minerals, pigments, pharmaceutical and other organic and inorganic compounds, is old, established, and reliable. With reference to remote sensing, the reasoning goes that if such could be done from air or space, it would give remote sensing a similar capability.

SENSORS - THE COLLECTORS OF RADIATION

With reference to systems development, the first steps were taken in the late 1940s and the 1950s when the Army, along with other groups, divided the photographic portion of the electromagnetic spectrum, 400 to 900 nm, into narrower bandpasses by means of various combinations of photographic emulsions and filters. The goal was to improve techniques for detecting targets and mapping conditions such as camouflage, vegetation type, vegetation stress, soil moisture, flood damage, wetland boundaries, to name a few, and the term multiband photography came into being to describe these efforts (Rinker, 1975). The Camouflage Detection Film developed by Eastman Kodak in WW II to distinguish between green vegetation and green paint is one example of a successful film/filter combination. This film later evolved into the popular Ektachrome Infrared film; and, the bandpass/dye associations passed into the digital domain of Landsat as the False Color Composites. The bandpasses were still broad, however, ranging from 60 to 100 nm. Nevertheless, multiband photography had applications to some forms of targeting, and change detection.

Next came the Landsat Multispectral Scanner, which recorded reflected sunlight in four broad bands - two in the visible, each of which is 100 nm wide, and two in the in-frared, with one being 100 nm wide and the other 1.1 micra. This was followed by the Thematic Mapper with six bands in the reflected solar region, and one band in the thermal infrared, with the narrowest band being TM band 3 at 60 nm. Whatever spectral variations occur in the terrain within any of these bands are averaged out to arrive at a digital number (DN) representing the brightness for the whole band. Extensions of the multispectral concept into the thermal infrared region of the spectrum include the Advanced Very High Resolution Radiometer (AVHRR), and the airborne Thermal Infrared Multispectral Scanner (TIMS) developed by Daedalus Enterprises, Inc.

In the early 1980s, a system came forth that greatly altered the existing concepts of multispectral remote sensing with reflected solar energy. This was the Airborne Imaging Spectrometer (AIS) developed by the Jet Propulsion Laboratory (JPL). Details of this system and some of the application results can be found in reports by La Baw, 1983, Vane and Goetz, 1985, and Vane, 1987. The AIS records reflected solar energy in some 128 channels, or images, within the 1.2-2.4 micra region of the spectrum and with a spectral bandwidth for each channel of less than 10 nm. The AIS evolved into the AVIRIS with some 220 raw data channels, or images, within the 0.4-2.45 micra portion of the spectrum. Resampling gives 210 spectral bands of radiometrically calibrated

data. The instantaneous field of view (IFOV) is 1 milliradian, or about 10 meters at operational altitude. Each image is a record of the intensity of reflected sunlight within a spectral bandwidth of less than 10 nm. After calibrations and corrections have been made, the intensity values of the 210 channels, for any given picture element (pixel), can be called up and displayed in sequence along the wavelength axis, as a spectrophotometric trace, i.e., radiometric intensity versus wavelength. Because of the narrowness of the bands, as well as their multiplicity, these systems are called hyperspectral, to differentiate them from the broad band systems, e.g., MSS, TM, SPOT, etc.

HYPERSPECTRAL - WHAT IS IT?

As indicated, hyperspectral refers to a multiplicity of recording channels that have relatively narrow bandwidths. Since the advent of the AIS and the AVIRIS, other airborne narrow bandpass systems have been developed, and plans laid for satellite follow-ons. The latter include the Shuttle Imaging Spectrophotometer Experiment (SISEX), and the High Resolution Imaging Spectrometer (HIRIS). Details of these systems can be found in a Proceedings Issue of the Society of Photo-Optical Instrumentation Engineers (Vane, 1987b). Table 1 lists a number of multispectral and hyperspectral systems and shows the trend towards increasing numbers of channels. Table 2 shows bandwidth characteristics of some of the systems.

Figure 1 portrays the hyperspectral concept. The stack of images, 210 in the case of AVIRIS, forms an image cube. The X and Y axes relate to ground, or pixel location, and the third axis to wavelength. Because of the Army's interest in natural and man-made surfaces, it must be able to work with diverse remote sensor data, and the wavelength axis of its image cube should extend from the ultraviolet, through the reflected solar, thermal infrared, and microwave regions, out to at least L-band radar at about 23.5 cm wavelength, as shown in the figure. Moreover, the Army must be concerned with all photons - reflected, emitted, and luminesced - and be able to move back and forth along the image cube axis, incorporating, evaluating, and comparing whatever imagery bands and other data are available, such as Digital Terrain Elevation Data (DTED). Once the corrected image files are in the computer, the spectral patterns can be evaluated by placing the cursor on the site of interest and bringing up a record of the DN values of each of the involved channels. As a minimum, these data should be able to be displayed as line spectra, intensity versus wavelength spectra, and, in the case of luminescence, as three-dimensional spectra (intensity, excitation, emittance), and as contour plots. The spectra can be evaluated in a number of ways, either directly, or by comparison to a computer library of spectral data bases and models.

Figure 2 is an image cube display of an AVIRIS image over Moffett Field, California. The wavelength axis extends downward. The number 2 on the cube image indicates that it is a record of reflected sunlight in the second, or the 410-420 nm bandpass (approximately). The stack of thin lines parallel to the image and extending downward like pages of a book, are the edges of the other images, i.e., channels 11, 12, 13,... . The strong variations in the edge intensities are due to atmospheric absorption caused mostly by water vapor and oxygen. The dark zone indicated by the arrow consists of four images taken in the atmospheric water absorption bands at 1.35, 1.38, 1.41, and 1.46

micra. With solid and liquid samples, the four bands merge into one broader band centered at about 1.4 micra (refer to Figure 4). Because the atmosphere absorbs many wavelength components of the incoming sunlight, as well as of the reflected energy en route to the sensor, corrections are needed for many targets. If one is interested in vegetation stress, this involves the depths and shapes of a number of water absorption bands. Because water vapor is a component of the atmosphere, the analyst does not know how much of the depth and shape of those water bands is due to atmospheric absorption, and how much is due to vegetation absorption. If corrections can be made to remove the atmos-mospheric component via available models such as LowTran, then the residuum can be attributed to plant water.

TABLE 1 - MULTISPECTRAL AND HYPERSPECTRAL SYSTEMS. Some operational and planned multispectral and hyperspectral systems, and the number of bands over which they collect spectral data. In general,as the number of bands increases, the spectral bandwidth decreases.

SYSTEM	MAKER	BANDS	NAME
			OPERATIONAL
MSS	HUGHES	4	LANDSAT MULTISPECTRAL SCANNER
SPOT	FRANCE	4	SYSTEME PROBATOIRE D'OBSERVATION DE LA TERRE
TIMS	DAEDALUS	6	THERMAL INFRARED MAPPING SCANNER
TM	HUGHES	7	LANDSAT THEMATIC MAPPER
NS-001	JPL	8	THEMATIC MAPPER SIMULATOR
ATM	DAEDALUS	11	AIRBORNE THEMATIC MAPPER
ATIS	GER	12	AIRBORNE THERMAL IMAGING SPECTRORADIOMETER
GEOSCAN	GEOSCAN	24	(AUSTRALIAN SYSTEM)
ASAS	JPL	30	ADVANCED SOLID STATE ARRAY SPECTRORADIOMETER
GERIS	GER	63	GEOPHYSICAL ENV. RES. IMAGING SPECTROMETER
AIS	JPL	128	AIRBORNE IMAGING SPECTROMETER
AVIRIS	JPL	224	AIRBORNE VIS. AND INFRARED IMAGING SPECTROMETER
			UNDER DEVELOPMENT OR AWAITING LAUNCH
SISEX	JPL	196	SHUTTLE IMAGING SPECTROMETER EXPERIMENT
HIRIS	JPL	192	HIGH RESOLUTION IMAGING SPECTROMETER
NIMS*	JPL	204	NEAR INFRARED MAPPING SPECTROMETER
VIMS*	JPL	320	VISIBLE AND INFRARED MAPPING SPECTROMETER

* = PLANETARY PROGRAM

TABLE 2 - BANDWIDTH CHARACTERISTICS. General bandwith and resolution characteristics of some of the systems listed in Table 1. IFOV stands for Instantaneous Field of View expressed in milliradians. GIFOV stands for Ground Inst.ntaneous Field of View at operational altitude expressed in meters.

SYSTEM	NO. OF BANDS	SPECTRAL RANGE (MICRA)	BAND WIDTH (nm)	IFOV (mRAD)	GIFOV (ALT) (m)
MSS	4	0.5-0.6	100	0.1	70
		0.6-0.7	100		
		0.7-0.8	100		
		0.8-1.1	300		
TM	7	0.45-0.52	70		30
		0.52-0.60	80		
		0.63-0.69	60		
		0.76-0.90	120		
		1.55-1.76	200		
		2.08-2.35	270		
		10.4-12.5	2100		
TIMS	6	8.2-8.6	400	2.5	
		8.6-9.0	400		
		9.0-9.4	400		
		9.4-10.2	800		
		10.2-11.2	1000		
		11.2-12.2	1000		
ASAS	30	0.45-0.87	14	0.86	
GERIS	63	0.4-2.5			
AVIRIS	220	0.41-2.45	9.6	1.0	20
SISEX	196	0.4-2.5	11	0.12	30
HIRIS	192	0.4-2.5	10		30

Figure 3 shows a subset of AVIRIS images over the USAETL/U.S. Geological Survey (USGS)/U.S. Department of Agriculture (USDA) field site at the Jornada Experimental Range near Las Cruces, NM. These are three of the 210 images that can be displayed.

The notion has been expressed that this is overload, and that such a multiplicity of bands will lead to data constipation in the collection system, the transmission system, and the data reduction and manipulation systems; and, to ease this, unneeded bands should be eliminated from the collection system. If one thinks of hyperspectral imagery as an extension of Landsat, and plans to use the techniques of band rationing throughout the 220 channels - then, as far as the data reduction and data manipulation systems go, constipation is at hand. The important point is that, although such band ratioing can be done, one can go to a direct call-up of the spectral reflectance plot for any selected area. Nevertheless, reducing the number of channels is thought to be desirable by a number of agencies. But, which ones can be eliminated - which ones are unneeded? If you have a narrowly defined goal, the question is easier to answer. For targeting minerals, the geologist can get by with perhaps

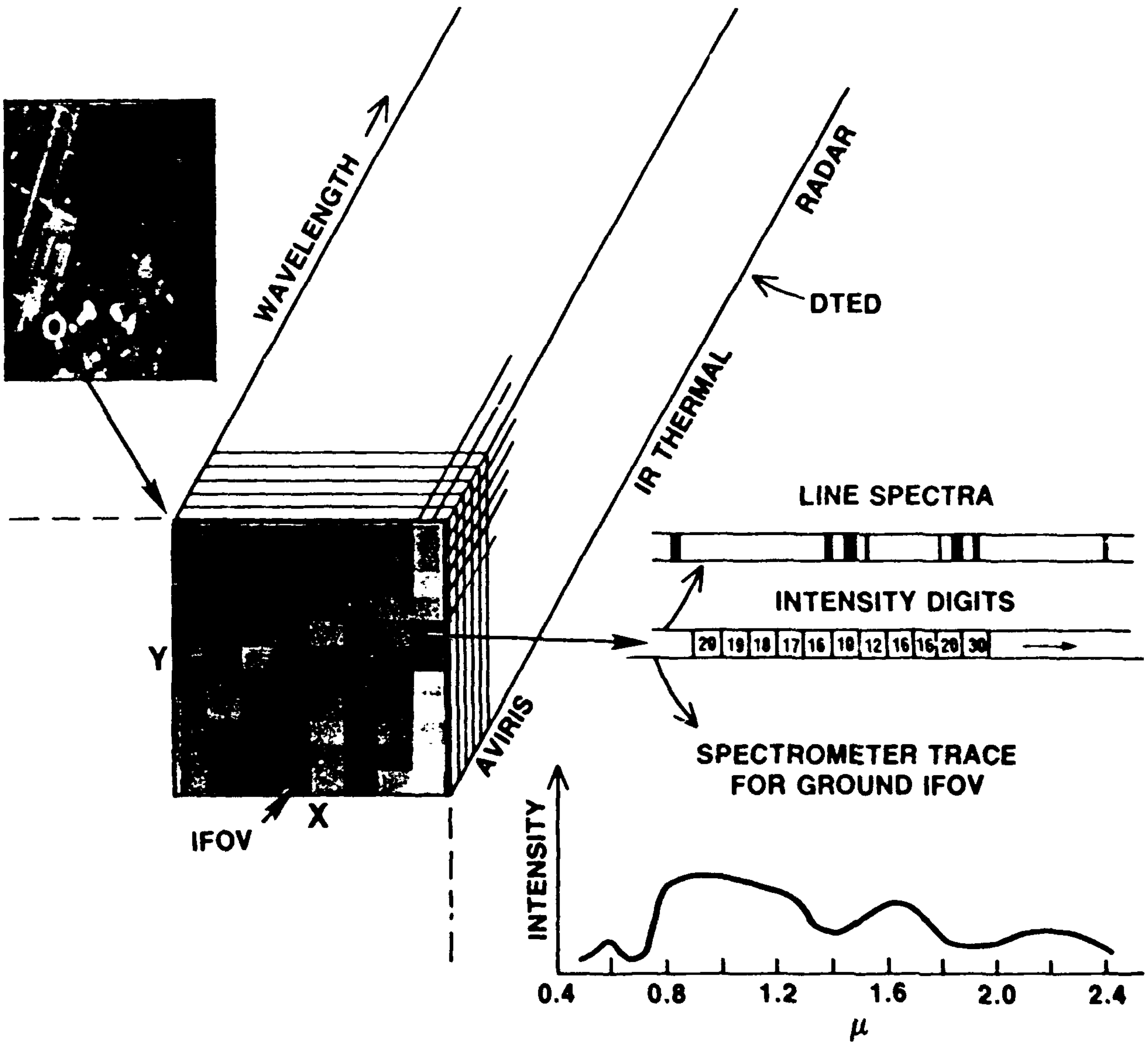

FIGURE 1 - IMAGE CUBE SCHEMATIC. On the image cube, X and Y indicate ground coordinates, and the third axis is wavelength. For Army purposes it should extend from the ultraviolet out to L-Band radar at 23.5 cm and be able to incorporate other data such as DTED. For any pixel, marked by the cursor, one can sequentially display the intensity values for the bands involved, e.g., MSS, TM, TIMS, AVIRIS, HIRIS, etc., as a line display or as a radiance plot of intensity versus wavelength. These can be compared to computer stored spectral data bases to arrive at probable identities. Or, the scene can be searched for all locations that are a spectral match, within some variance range, for a given spectral signature.

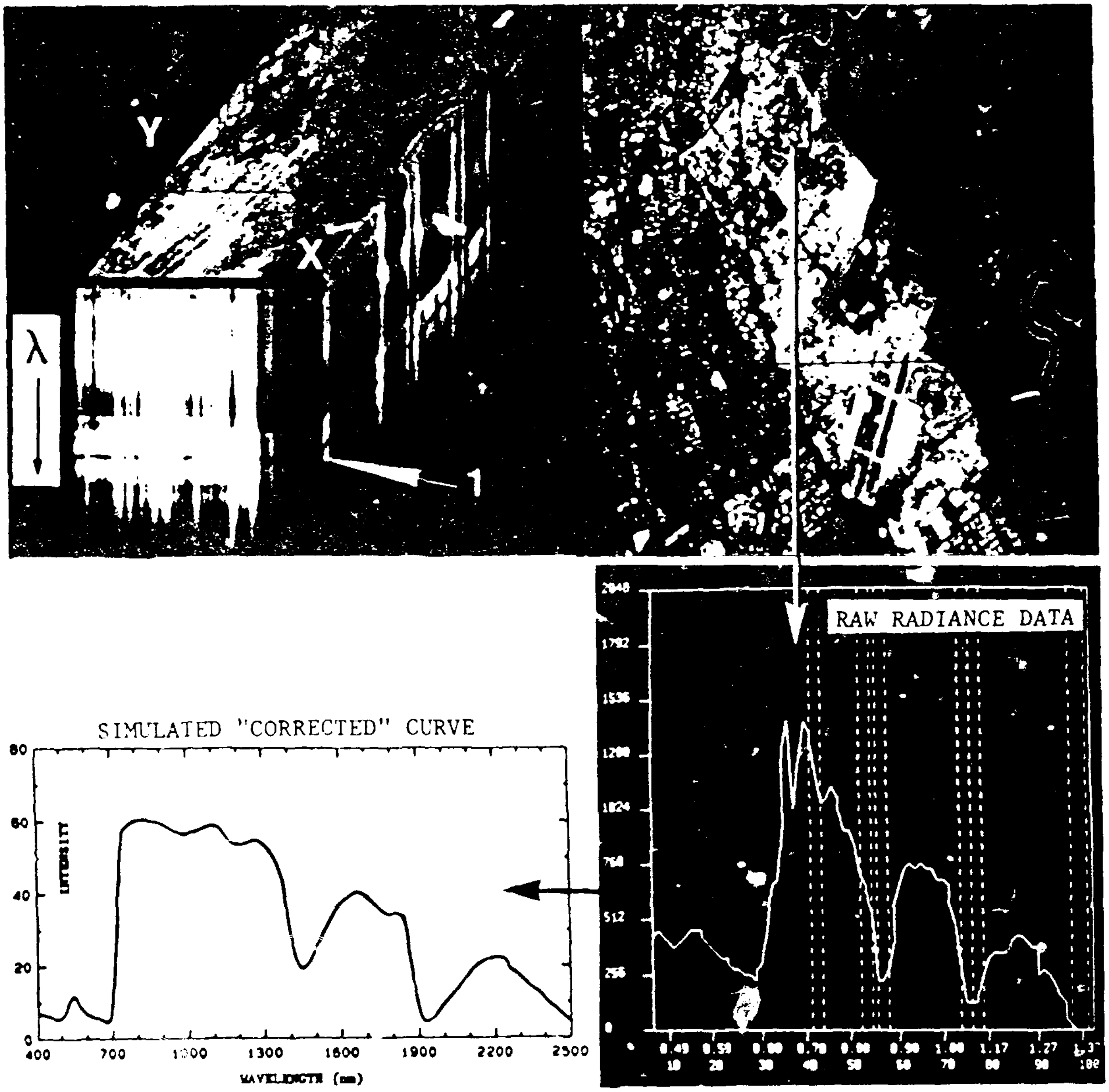

FIGURE 2 - AVIRIS IMAGE CUBE. AVIRIS image of Moffett Field Naval Air Station area, Sunnyvale, CA, taken on 25 June 1987 by JPL. This display was formed on the PIXAR by Barry Holecheck at USAETL. Here, the wavelength axis is vertical. The dark zone indicated by arrow no. 1, consists of four images in the water absorption bands at 1.35, 1.38, 1.41, and 1.46 micra. To the right is a black and white print of a color composite image. The graph displays the pixel intensities between 0.4 and 1.37 micra for the vegetated area indicated in the image. Although uncorrected for atmospheric absorption, the pattern is typical of chlorophyll. The vertical dashed lines mark atmospheric absorption bands. The absorption band, just beneath the arrow going down from the image, is caused by oxygen. Its dashed line did not record in the photograph. The others are due to water vapor. Once corrected, the oxygen band would be eliminated as well as most traces of the water bands clustered at about .89 and 1.1 micra, and other intensities would be adjusted. The result would be analogous to the simulated curve at the left.

FIGURE 3 - AVIRIS IMAGERY. This imagery was taken by the National Aeronautics and Space Administration (NASA)/JPL on 31 May 1989 over the USDA Jornada Experimental Range near Las Cruces, NM. The images are channels 20, 30, and 40, i.e., images of 9.6 nm bandwidths centered at about 592, 688, and 784 nm. In addition to a data base of some 60 years of records kept by the USDA on vegetation, soils, erosion, etc., USAETL and the USGS/Flagstaff group have installed an instrumented test site that continuously records meteorological and radiometric measurements, and have developed an extensive library of spectral reflectance field measurements. These data sets form the basis for developing hyperspectral digital analyses techniques.

30 to 40 bands. For determining crop quantity and quality, the agriculturalists can get by with perhaps 30 bands, only a portion of which overlap the geologists needs. The Army, however, has broader interests in terms of terrain, targeting, and intelligence, and has need for information about identities, conditions, and properties associated with vegetation, soils, rocks, minerals, and cultural objects including camouflage. Without doubt, some reduction can be made - perhaps bands that have no use for anybody - but, it is too early for such determinations.

There is another important benefit to an imaging spectrometer. It provides two domains of information for evaluation - image patterns and spectral patterns. From the standpoint of terrain information in terms of materials identities and conditions, potential for dust generation, location of engineering materials, engineering site selection and evaluation, probable locations of ground water, subsurface waste disposal, etc., the manual analysis of stereo imagery is still state-of-the-art. For example, an area can be covered with a vegetative mantle of grass and trees, and all that the spectral data will show will be reflectance traces of chlorophyll. In stereoscopic viewing, however, the shapes of the landform and drainage patterns can reveal that beneath the vegetal mantle rests a thinly interbedded series of limestones and shales dipping gently to the west, and with unstable colluvial materials on the lower slopes. At present, imaging spectrometers provide only monoscopic imagery, so there is a reduction in the quantity and quality of information that can be derived on the basis of image pattern shapes; but, these shapes are present, and they can make significant direct contributions to an analysis, as well as assist in the evaluation of the spectral data. Furthermore, existing routines for combining bands to make color composite images, such as Landsat, or the Coastal Zone Color Scanner (CZCS), can be directly applied to hyperspectral data.

In any event, the airborne imaging spectrometers are here, the space borne systems are in development, and the hyperspectral concept is sound. For the Army, the issues to be resolved include: what are these systems suited for? - what are their advantages, disadvantages, and limitations? - and, how well will they work?

HYPERSPECTRAL - WHAT CAN IT DO?

The spectral data for the imaging spectrometers can be evaluated on the basis of: shape of the overall curve, or portions of it; intensity differences and ratios at any selected wavelength range; wavelength location of absorption bands; and, depth and shape of absorption bands. To link these to identities and conditions requires an extensive computer library of field and laboratory measurements of spectral reflectance, luminescence, and emittance throughout the reflected solar, and thermal infrared portions of the spectrum - and the software to make the evaluations and comparisons. USAETL has developed a spectral reflectance/luminescence data base of over 1,000 samples of soils, rocks, vegetation and the seasonal factors that influence them. Such a library needs excellent documentation, because these measured values change with a variety of factors. For any given surface, the molecular makeup determines the basic characteristics of absorption, reflectance, luminescence, and emittance. These in turn, are modified by the structure of the surface, its orientation in relation to the sensor and to the illuminating source. For example, maintaining a constant field of view and a constant viewing angle,

while measuring spectral reflectance at different sun angles and elevation, can result in variances of plus or minus ten percent. With reference to structure, vegetation can have smooth, crenelated, or wrinkled leaf surfaces, and the leaves and stems can have many different sizes and be arranged in many different ways. This means different highlight/shadow ratios, different amounts of transmitted and re-reflected infrared energy through the biomass, and different amounts of radiation reflecting up through the vegetation from the soil surface (Satterwhite and Rinker, 1986).

For a given mineral composition, the spectral signature of a fine textured soil can differ from that of a coarser textured soil. Then, there are the influences of conditions - a term used to denote such things as age, growth phase, wet, dry, weathered, lichen covered, etc. New leaves have a different spectral signature than older leaves, wet soil is different than the same soil when dry, a weathered rock surface differs from a fresh surface. In reality, these are different chemical forms, which gets back to the earlier statement that the molecular makeup of a surface establishes the basics of reflectance and absorptance. Keeping the target surface and illumination/sensor angles constant, the spectral signature is further modified by climate, season, and meteorological variations. Changes in incoming short and long wave radiation from space, wind, and atmospheric pressure greatly alter signatures and target/background contrasts in thermal imagery.

Multiplicity of measurements is necessary because there can be significant variation within any given class of targets, especially in field measurements. For example, one can measure 20 creosote bushes that look alike and are about the same size and age. But, the result will likely contain different reflectance spectra, with plus or minus ten percent variance, or more, from a derived norm. The variations are mostly in intensity, not in wavelength of absorption bands. Although the plants look alike, they are not identical - each has some variance in biomass, structure, openness, etc. These factors alter the characteristics of the energy reflected from the vegetal surfaces, as well as the characteristics of the contributing reflected soil component passing through, or reflected from the canopy.

For current systems and typical target areas, the IFOV (10 meters for AVIRIS) encompasses a mixture of surfaces, and the resulting spectral signature is a composite of individual signatures - which presents another problem in relation to digital analysis of spectral data.

Figure 4 shows examples of spectral reflectance measurements and indicates some of the more common absorption bands. By calling up the radiance plot of an area on a hyperspectral image and comparing it to a spectral measurements library, one can identify the surface material of that area. At least that is the intent; and, under certain conditions, and for certain materials, it can presently be accomplished. Extensive research remains to be done, however, before the technique can be routinely and successfully applied, regardless of material type, location, or season. Basic to such a procedure is an extensive and thoroughly documented library of field and laboratory spectral reflectance and luminescence measurements, coupled, where possible, to physical and chemical measurements.

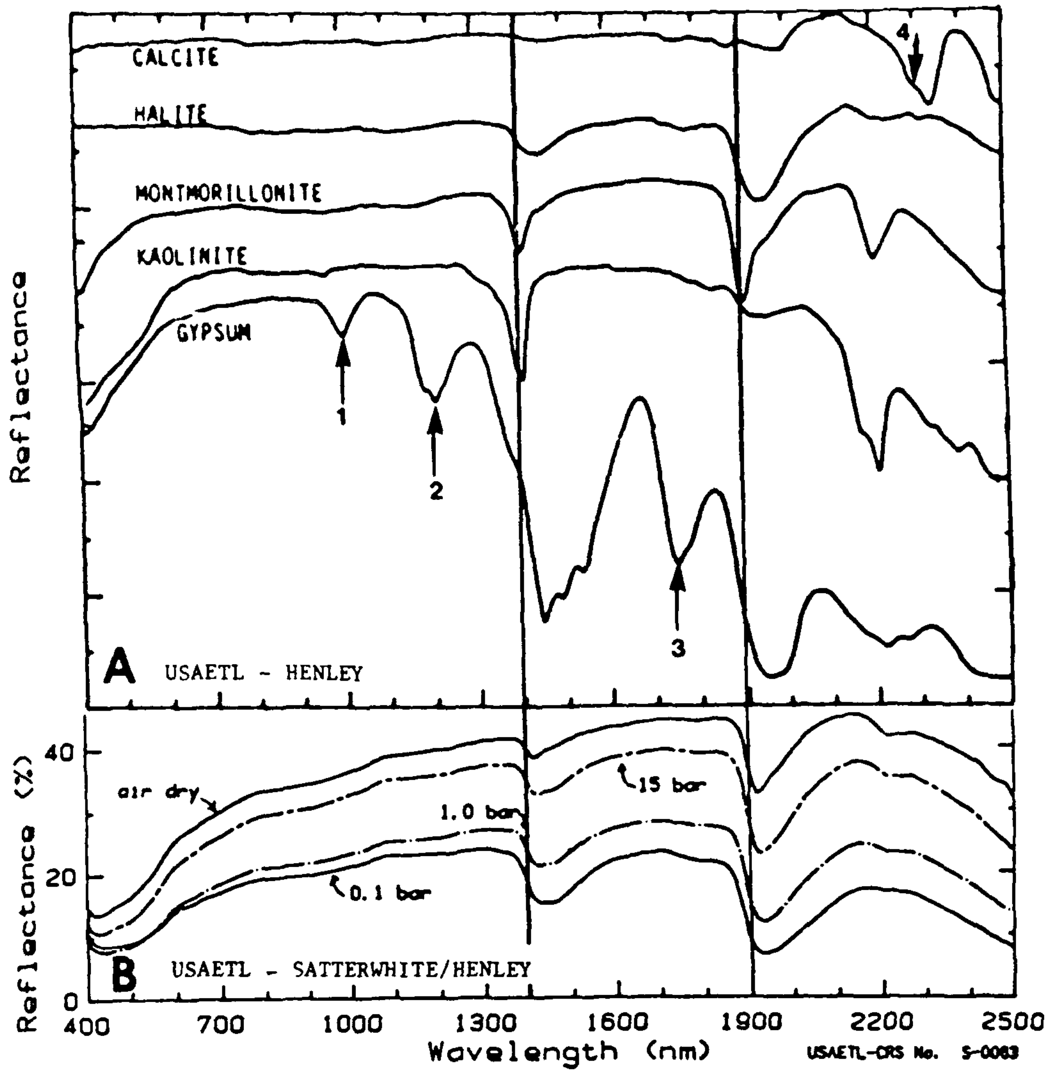

FIGURE 4 - PLAYA SURFACE REFLECTANCES. A. Reflectance measurements of playa surface minerals (Henley, 1988). The records are offset vertically to avoid overlap. The strong water absorption bands at 1400 and 1900 nm are apparent. When both are present, it indicates undissociated water (water of hydration, trapped water in the lattice). Kaolinite shows strong hydroxyl absorption at 1400 and 2200 nm but little at 1900 nm, which suggests a lack of bound water. Molecular water is important in gypsum, and its overtones and combinatorial tones account for the bands at 1000, 1200, and 1700 nm (arrows 1, 2, 3). Calcite is fairly featureless except for the carbonate molecular vibration band at 2300 nm (arrow 4), and sometimes a weak band at 2000 nm. B. Influence of moisture on a silty loam playa soil from Broadwell Lake, San Bernardino, April 1988 (Satterwhite and Henley, in edit).

The first application example illustrates the need for both reflectance and luminescence spectra. Figure 5-A shows the reflectance characteristics of two fabrics, A and C, and of a typical green leaf, curve B. Note the deep water absorption bands at approximately 1.4 and 1.9 micra, which are typical of green turgid vegetation. Fabric C is a reasonable match in the visible and out to about 1100 nm. But, it distorts the 1400 nm water absorption band, misses the 1900 nm band, and would be easy to detect. Fabric A, however, mimics the vegetation throughout the spectral range. Based on the reflectance spectra, it would not be detectable against a vegetal background, and would, in fact, be classified as vegetation. At this point, one needs other spectral information, such as luminescence, or infrared thermal emittance. Figure 5-B shows the luminescence characteristics of these materials. For these measurements, the surface is illuminated with a narrow band of energy at a given wavelength (called "excitation"), and the surface scanned for the spectral distribution of any luminesced photons. This step is repeated at successive wavelength increments of excitation energy until the spectrum of interest has been covered. The result is a three-dimensional plot of excitation wavelength versus emission wavelength versus intensity, similar to Figure 6-B. In Figure 5-B, the luminescence intensities of the fabrics, vegetation, and soils were plotted for the indicated Fraunhofer lines. Fabrics A and C not only have strong signals as compared to soils and vegetation, but have different distributions. Thus, they would be detectable in a milieu of soil and vegetation, and also distinguishable from each other. When bruised, the vegetation showed a strong luminescence that persisted for hours, indicating a possibility for detecting passage of traffic.

Figure 6-A shows the reflectances of four differently dyed areas of a fabric. Although they, or their composite signal, would be distinguishable against a background of vegetation, the contrast would not be strong against a mixture of soil and different vegetation types and conditions. On a luminescence basis, however, the fabric has a signal whose intensity not only greatly exceeds that of soils and vegetal backgrounds, but occurs at different wavelengths - making detection a certainty if the areal extent is sufficient. These relations are shown in graphs B and C. The signal threshold for airborne detection is about 1,500 units, and the fabric's luminescence peak is 81,000 units. In general, the luminescence seldom goes above 12,000, for healthy vegetation. As vegetation senesces, the luminescence increases, but rarely reaches 20,000. The vegetal sample in Figure 6-C, has a peak of 11,000. The iso-intensity contour plot, graph C, shows that the luminescence of the two samples, vegetal and fabric, occurs in different wavelength bands.

Figure 7 shows some of the differences that take place in vegetal luminescence as a function of drying and of aging. For the samples we have measured so far, these seem to be characteristic features. In each example, the upper graph is a three-dimensional display of emission versus excitation, and the lower graph is an iso-contour plot. Figure 7-A is typical of healthy, turgid, green leaves. Symbolic of this condition are the five distinct luminescence peaks indicated by the small numbered arrows, 1 through 5. Peak no. 5 has the highest intensity. Figure 7-B shows the effects of drying beyond the wilt stage. Peaks 2, 3, and 5 have disappeared, and a new peak, no. 6, has developed. In addition, the intensity of peak no. 1 has decreased. Figure 7-C shows the effects of senescence. Peaks 1, 2, 3, 4, and 5 are gone, peak 6 is present, and peak 7 has been added. Table 3 summarizes these results. Green, wilted vegetal material also shows some luminescent changes.

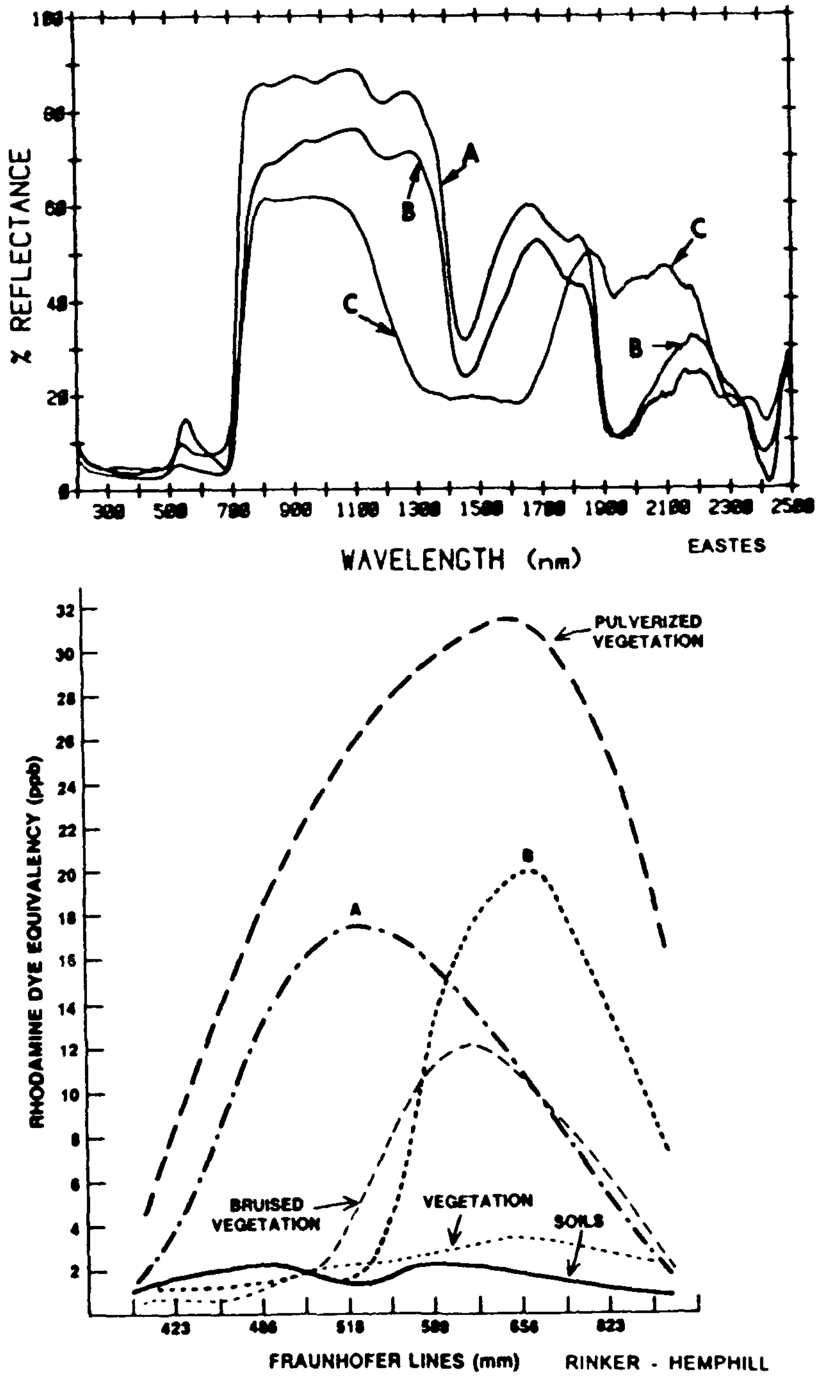

FIGURE 5 - FABRIC AND VEGETATION REFLECTANCES. At the top are spectral reflectances of two fabrics (A and C) and a green leaf (B). The measurements were taken by J.W. Eastes (USAETL). Fabric A mimics vegetation, including the water absorption bands, and would be indistinguishable from it. Fabric C is a poor match, and would be easily detected. The lower graph is a plot of luminescence intensity in the Fraunhofer lines of the airborne FLD. These measurements were taken by J.N. Rinker (USAETL) and W.R. Hemphill (USGS). Both fabrics show in strong contrast to soils and vegetation (bottom two traces), and also differ significantly from each other. Bruised vegetation gave a strong luminescence signal that persisted for many hours. Pulverized vegetation had even a higher intensity.

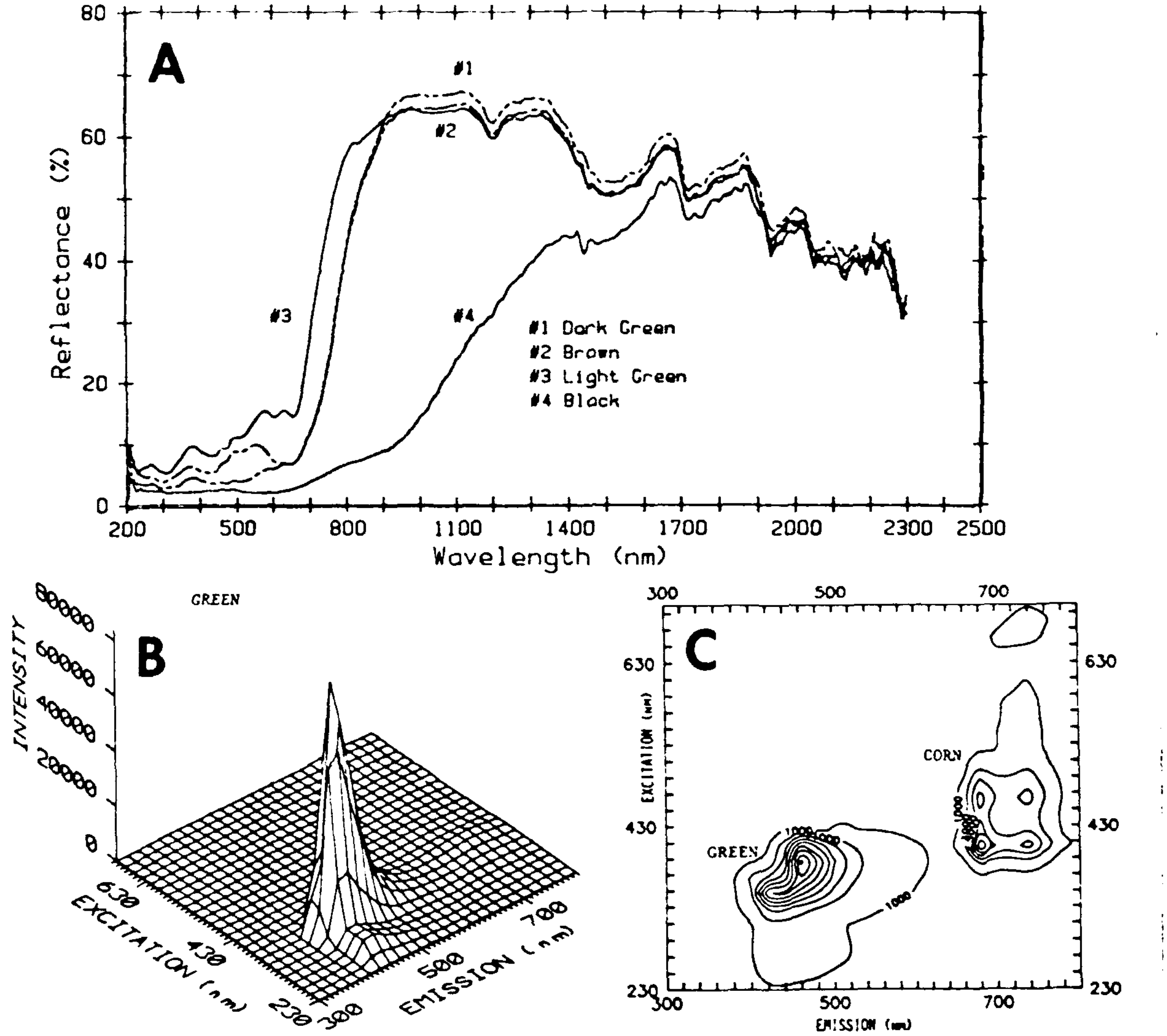

FIGURE 6 - COMPARISON OF FABRIC REFLECTANCE AND LUMINESCENCE. At the top are the reflectance characteristics of four dyed areas of a fabric. Although distinguishable from vegetation, there would not necessarily be a strong contrast, especially if the background provided a mixture of soils and different types and conditions of vegetation. Graph B is a luminescence plot of the green fabric, showing an exceedingly high signal, some 81,000 units. The detection threshold is considered to be 1,500 units. Graph C is an isointensity contour plot of the green fabric and of corn, which gives a response typical of healthy herbaceous vegetation. Against the 11,000 intensity units for typical herbaceous vegetation, and the flat response of soils, the fabric with its 81,000 intensity units is easily discernible. It would likely be the brightest object in the scene. This high intensity is probably due to brighteners in the laundry products, as unwashed cloth does not give such a signal. Measurements by M.B. Satterwhite (USAETL).

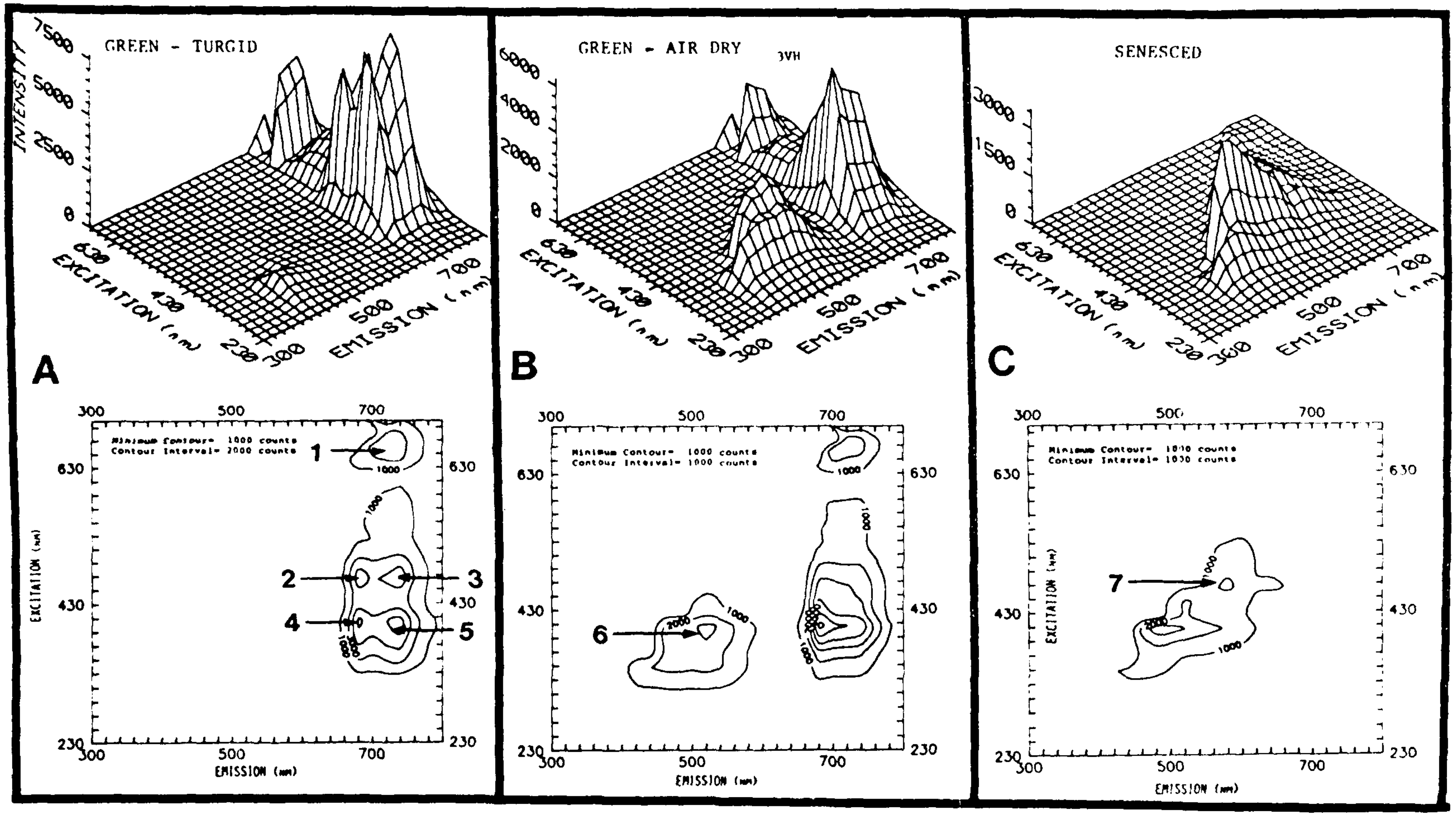

FIGURE 7 - VEGETATION LUMINESCENCE CHARACTERISTICS. Alteration of vegetal luminescence characteristics as functions of drying and aging. For samples measured so far, these are representative attributes. The upper graphs are three-dimensional displays of excitation wavelength versus emission wavelength versus intensity of the emission signal. The lower graphs are iso-contour plots of the same information. Set A shows the five distinct luminescence peaks (arrows 1-5) characteristic of healthy, turgid, green leaves. With loss of plant water (graph set B), peaks 2, 3, and 5 disappear, and a new peak (arrow 6), develops. Set C shows the effects of senescence. The original peaks (1-5) are gone, peak 6 is present, and peak 7 has been added. Measurements by M.B. Satterwhite (USAETL).

TABLE 3 - LUMINESCENCE BAND CHARACTERISTICS OF VEGETATION. Approximate locations of peak luminescent intensities for healthy green vegetation (H), air dried vegetation (AD), and senesced vegetation (S), as taken from the contour plots in Figure 7. The numbers express the excitation and emission wavelengths in nanometers (nm).

Excitation (nm)	Emission (nm)	H	AD	S
1. 660	730	X	X	
2. 470	680	X		
3. 470	730	X		
3. 400	680	X	X	
4. 400	730	X		
5. 400	500		X	X
6. 470	580			X

So far, the wilt changes do not seem of sufficient magnitude to be diagnostically useful in airborne remote sensing. When coupled to reflectance spectra, however, such a distinction might well be possible. Green turgid vegetation has fairly deep water absorption bands at 1.4 and 1.9 micra. These decrease in depth with loss of plant water, and thus can serve as probable indicators of this condition.

An interesting observation was made by W. Hemphill/USGS (private communication), that when looking out over the terrain with the FLD instrument, there was a strong luminescent signal just above the horizon. It was during the pollen season, and he wondered if the two were connected. Subsequent measurements at USAETL confirmed the possibility, as shown in Figure 8. Implicit in this illustration are a potential application and a potential problem. First, a possible technique for detecting and monitoring airborne pollen loads, i.e., measuring atmospheric quality; and second, a resulting problem - i.e., such an airborne load can reduce contrast, or otherwise interfere with the recording of terrain surface signals.

All materials have spectral reflectance characteristics; but, not all materials have luminescence characteristics. Although we have examined but a portion of what is available, some general statements can be made. Soils measured to date do not show useful luminescence. About 75 percent of the vegetal samples and 30 percent of the fabrics have detectable and diagnostic luminescence peaks. For healthy turgid vegetation, the luminescent peaks fall in the wavelength range between 640 and 800 nm. As vegetation dries out, these peaks decrease in intensity and peaks develop in the wavelength region between 400 and 600 nm. Intensity distributions are related to material type and condition, and the peak intensities can be sorted into fairly distinct groups based on emission wavelengths. As shown in Figure 9, healthy herbaceous vegetation falls into one assemblage, and everything else, e.g., paints, fabrics, pollen, dry vegetation, senesced vegetation, etc., falls in another. So far, with reference to peak emissions, there are three diagnostically useful excitance bands. These are centered at 400, 460, and 660 nm. The important emission bands are centered at approximately 690 and 730 nm.

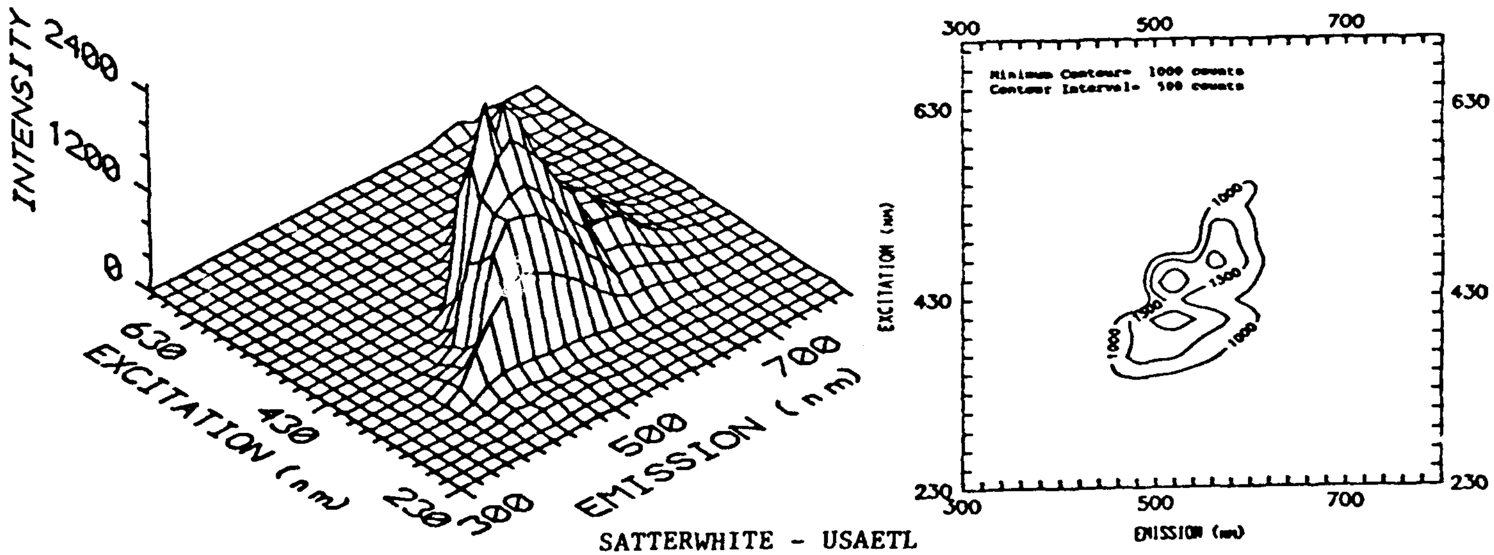

FIGURE 8 - LUMINESCENCE CHARACTERISTICS OF LOBLOLLY PINE POLLEN. Other pollens also luminesce. Pollen of scrub pine is barely detectable, whereas that of cattails has a signal stronger than that of loblolly pollen. Loblolly pollen, however, consists of very small particle sizes and is readily airborne. This suggests a potential technique for monitoring atmospheric components, and also a potential interference problem for collecting terrain data. Measurements by M.B. Satterwhite (USAETL).

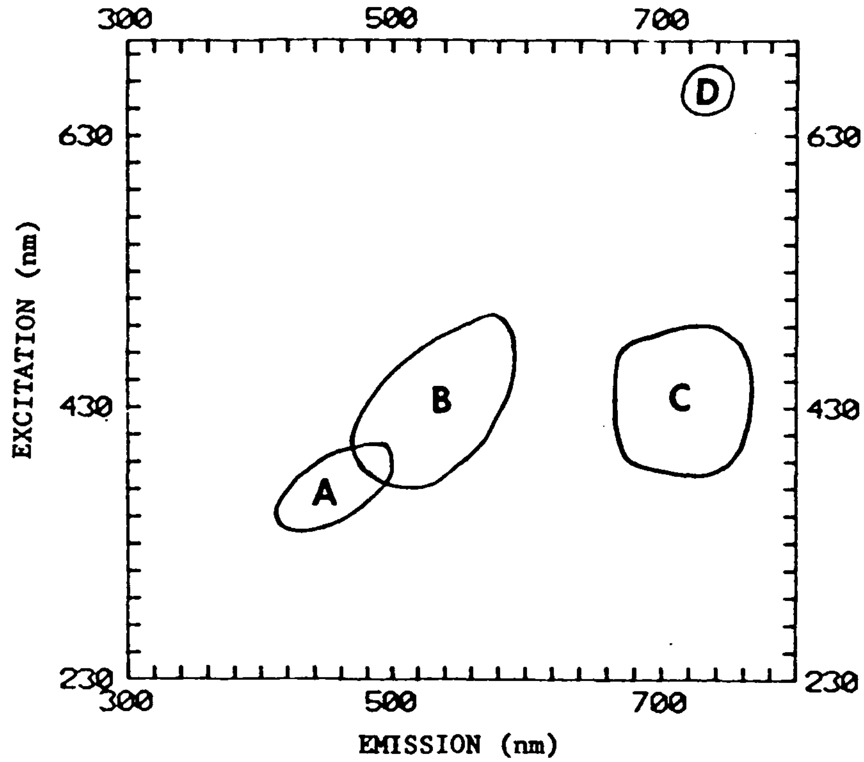

FIGURE 9 - LUMINESCENCE CLASSES. On a generalized basis, and for those materials that had usable luminescent peaks, the distributions of the peak intensities fall into the indicated areas. With one exception, so far at least, area A contains the fabrics. Area B, which overlaps A to some extent, contains the peaks of pollen, dry vegetation (pine and herbaceous), and senesced vegetation (pine and herbaceous). Area C contains the peaks of healthy vegetation (pine and herbaceous). Area D has a few secondary peaks associated with herbaceous vegetation. The most useful excitance bands are between 330 and 510 nm. The diagnostic emission peaks fall into two groups, 400-600 nm and 660-760 nm, with the latter containing all the healthy herbaceous samples.

SUMMARY

As stated at the beginning, targeting refers to the need to detect, identify, and evaluate objects and areas of concern to both military and civil needs. Examples of such endeavors include: military hardware and operational units; items such as traffic use, camouflaged positions, and change detection; vegetation typing and vegetation zones altered by aerosols, chemicals, pathogens, and drought; alteration zones or zones of mineralization; areal extent of damage and boundaries associated with flooding, fire, and other natural and man-induced disasters; and landscape alterations associated with climatic change. Towards these ends a number of interagency cooperative research efforts have been established. These include: desert processes, desertification and climatic change studies (USAETL/USGS/USDA/NASA); time varying thermal signatures, target/background thermal contrast modeling, and assisted target recognition (USAETL, USACRREL, USAF); camouflage detection and specialized

targeting (USAETL, USA Natick RD&E Center, USA Fort Belvoir RD&E Center); digital analysis techniques (USAETL, USGS, USDA); and disaster evaluation (USAETL, Canada/National Transportation Safety Board). The latter endeavor arose out of the Army's efforts in applying remote sensing techniques to the Gander, Newfoundland airplane crash in December of 1985 (Rinker et al., 1989).

In support of the hyperspectral program, USAETL is developing classification and analytical software; collecting extensive field and laboratory spectral measurements of soils, rocks, vegetation, and man-made materials; and, in cooperation with the USGS group at Flagstaff, AZ, maintaining a series of instrumented test sites that collect around-the-clock measurements of target/background radiation characteristics and concurrent meteorological conditions (Rice and Krusinger, 1985). The resulting data bases (Table 4) support empirical modeling, assisted target recognition, and digital analysis techniques for hyperspectral imagery.

Table 4. EXISTING DATA BASES IN THE USAETL INVENTORY. The temperate data base has eight years of continuous measurements; the subhumid, three and a half years; and the arid, one and a half years. The spectral data bases contain field and laboratory measurements of natural and man-made surfaces, and are collected with an equal or finer spectral resolution than that of the remote sensing hyperspectral systems. Thus, they can be averaged over any selected bandwidth to provide intensity values as they would be in Landsat MSS, TM, TIMS, AVIRIS, etc.

ETL Radiation/Meteorological Data Base - Temperate
ETL/USGS Radiation/Meteorological Data Base - Subhumid
ETL/USGS Radiation/Meteorological Data Base - Arid
ETL Spectral Reflectance Data Base - Solar Radiation (0.4-2.5 micra)
ETL Spectral Reflectance Data Base - Thermal Infrared (2.5-14 micra)
ETL Spectral Luminescence Data Base

The data bases and the imagery are but the beginnings. Software is being evaluated and/or developed for incorporating the data bases into the computer library; for sample/target classification hierarchies; for display formats, e.g., line spectra, intensity versus wavelength, three-dimensional plots, contour plots, etc.; and for targeting and analytical procedures. There are basic issues to resolve and tasks to be done that involve all the participants in the interagency hyperspectral working group. These include: establishing variances within sets; determination of significant spectral bands (statistical, mathematical, empirical); the importance of absorption band slope changes; atmospheric backout in relation to targets, areas, and conditions; self-calibration of imagery from known data base sets; mixed pixel problem; influence of steady state illumination on luminescence; and testing and validation of existing models.

The airborne systems are here, e.g., AVIRIS, FLD, and TIMS, needed spectral data bases exist, and enough hyperspectral image sets (solar reflectance, luminescence, thermal IR) have been evaluated by various interest groups to come to some general conclusions. NASA and JPL have shown the applicability

to targeting minerals. USGS, NASA, and USDA have shown applicability to minerals, petroleum, and vegetation stress. USAETL has shown applicability to military targeting. No technique is a panacea, no system does everything, and the hyperspectral, even in its broadest sense, has its limitations; but, from the standpoint of targeting, the technique has potential beyond any previous remote sensing endeavor.

Because of the diversity of requirements within the Army, and the varied activities in its laboratories, the Army has perhaps the largest diverse collection of radiation/meteorological, and spectral reflectance and luminescence data bases available, including associated empirical models and analytical techniques. Although these were developed to support military requirements, they can, without alteration, render direct assistance to critical national and worldwide problems such as narcotics, disaster evaluation, and global climatic change - problems that require all the talents and capabilities that can be brought to bear from both the military and civil domains.

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